PHYSIOLOGICAL EFFECTS OF EXPOSURE TO LOW CONCENTRATIONS OF CARBON MONOXIDE.[1]

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The effect of comparatively low concentrations of carbon monoxide for short periods and under normal air conditions of temperature and humidity, with the subject at rest, was studied by Dr. Yandell Henderson and his coworkers. In making recommendations to the New York and New Jersey Tunnel Commissions,[2] Doctor Henderson advised that if the Hudson River vehicular tunnel be so ventilated that persons passing through the tunnel would be exposed to not more than 4 parts of carbon monoxide in 10,000 parts of air for not longer than 45 minutes, they would experience no ill effects. This advice has been confirmed in supplementary experiments,[3] carried out by us in connection with studies at the Bureau of Mines Experiment Station at Pittsburgh.

In continuing our studies on low concentrations of carbon monoxide, we made a few experiments in a gas chamber where the conditions could be accurately controlled. The following factors were investigated:

1. The effect of long exposure in low concentrations of carbon monoxide.
2. The effect of strenuous exercise.
3. The effect of high temperature and humidity in low concentrations of carbon monoxide.

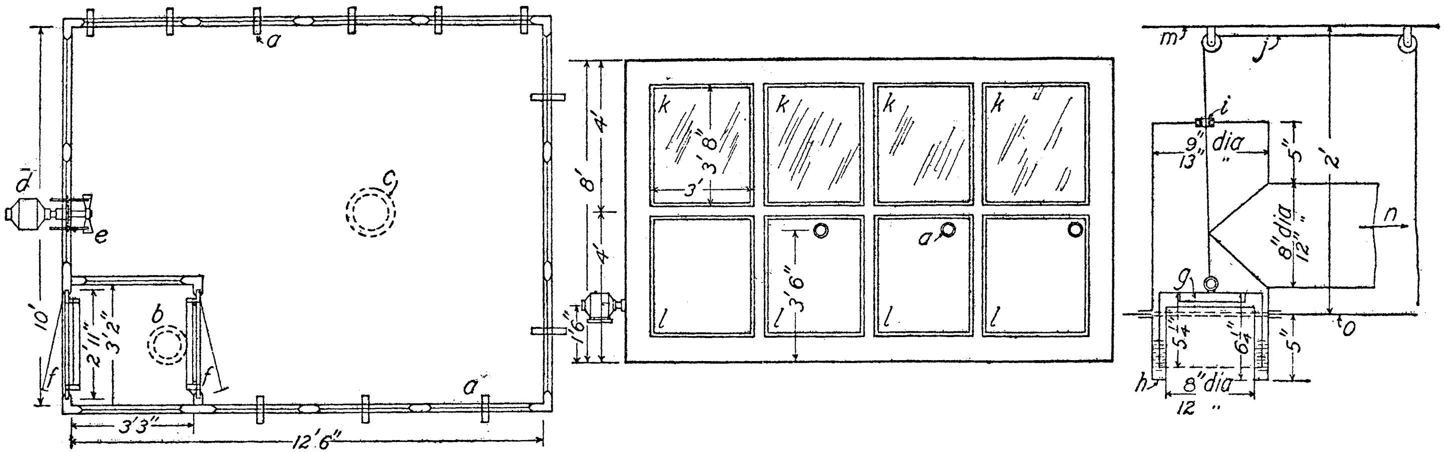
APPARATUS.

The work was conducted at the Pittsburgh Experiment Station, where a specially constructed gas-tight chamber (Pl. 1, A), 10 by 12½ by 8 feet, was available for such experimentation. Figure 1 shows the details of this room or gas chamber. The floor, walls, and ceiling are constructed entirely of sheet metal. The windows are of glass. The wooden doors, such as are made for large refrigerators, are lined on the inside with sheet metal, the edges are bordered with rubber, and the handles exert a clamping effect which fastens the doors tightly against their jambs. All metal joints are soldered. The glass windows are cemented in the metal sash with a putty containing

[1] Work done in cooperation with the U. S. Bureau of Mines.

[2] Report of Tunnel Gas Investigations (Problem 2: Physiological Effect of Automobile Exhaust Gases) made by Yandell Henderson, H. W. Haggard, M. C. Teague, A. L. Prince, and Ruth Wunderlich, published by the New York and New Jersey Tunnel Commissions, 1921.

[3] Appendix H, Physiological Data, by R. R. Sayers, H. R. O'Brien, F. V. Meriwether, and W. P. Yant in Report of Tests (Problem 4) Conducted in Experimental Mine Vehicular Tunnel, published by the New York and New Jersey Tunnel Commissions, 1922.

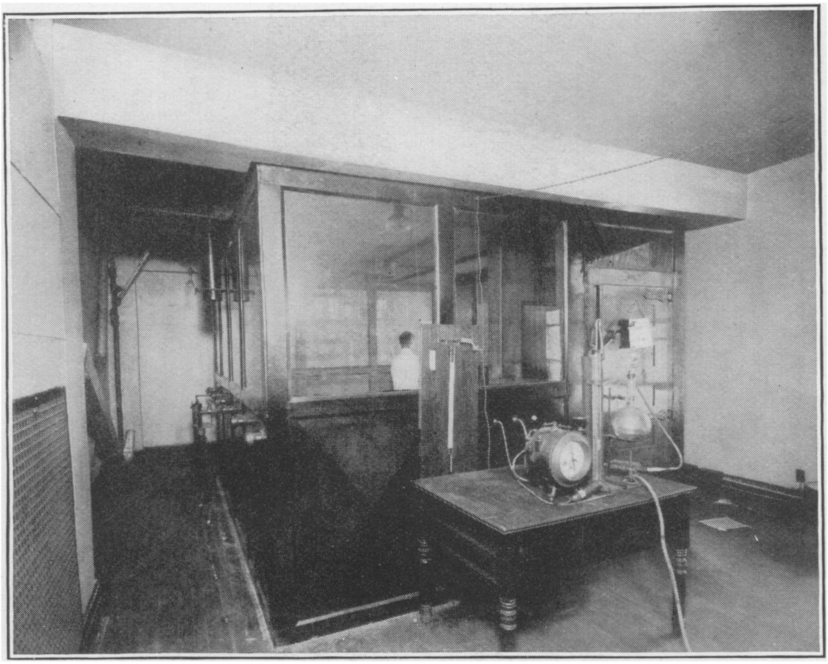


PLAN

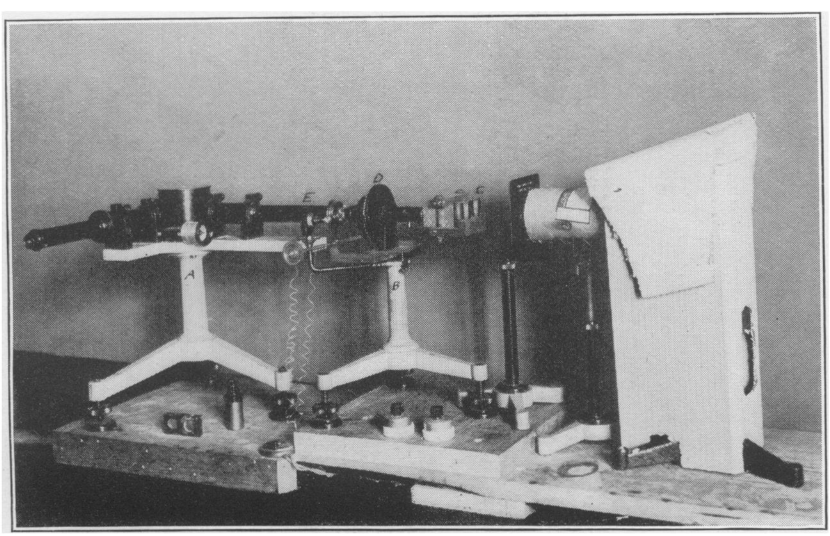
RIGHT SIDE ELEVATION

DETAIL OF FLUE VALVE

Fig. 1.—Details of the gas chamber used for experimental purposes at the Pittsburgh Experiment Station of the U. S. Bureau of Mines.



A. Gas chamber.



B. Spectrophotometer as set up for determination of carbon monoxide in the blood.

linseed oil and red lead, so that the joints between the glass and the metal are air-tight. Special valves are set in the roof for connecting the room with a flue leading to an exhaust fan. Each valve consists of a sheet-iron bell suspended in a tube of slightly larger diameter, which has an annular space containing mercury on the inside at the bottom. When the bell is seated in the annular space, the mercury seal makes the valve gas-tight. A chain attached to the bell runs over pulleys to a point where it may be reached on the outside of the chamber. Raising the bell into a closed space above a T in the pipe permits the gases in the chamber to be exhausted.

Experiments have shown that the room is nearly gas-tight. The interchange of gas between the inside and outside of the closed chamber during 24 hours amounts to less than 10 per cent of the chamber volume.

The "work" was done on a bicycle ergometer and calculated as foot-pounds. The carbon monoxide was made by dropping formic acid into hot concentrated sulphuric acid, and purified by passing through a soda-lime canister. An analysis of the gas used gave 99 per cent CO and 1 per cent air.

ANALYSIS OF BLOOD.

The analysis for the percentage saturation of the blood was made by the spectrophotometric method, described in detail in Appendix I, Report of Tunnel Gas Investigations No. 4, previously mentioned. In brief, this method is based on the observation that hemoglobin in combination with carbon monoxide has a power of absorbing light of certain wave-lengths different from that which it has in combination with oxygen, and that any mixture of the two combinations will show a proportional amount of that difference corresponding to the percentage of each in the mixture. By determining the extinction coefficient ($E = -\log$ transmission) of carbon monoxide hemoglobin and of oxyhemoglobin, we obtain a measure of their difference in absorption ($E_{CO} - E_{O_2}$). Then by finding the extinction coefficient, Ex, due to a mixture of these hemoglobins, such as would be found in the blood of a victim of carbon monoxide poisoning, we can calculate the percentage of each.

Let $E_{CO} - E_{O_2} = M$, a number representing the total increase of extinction due to carbon monoxide, and $Ex - E_{O_2} = N$, or $E_{CO} - Ex = N^1$, N representing value in extinction resulting from some of the hemoglobin having combined with carbon monoxide, or N^1 the value representing the possible extinction increase of that portion of hemoglobin which remained uncombined with carbon monoxide; then $\frac{N}{M} \times 100 =$ percentage of CO–Hb or $\frac{N^1}{M} \times 100 =$ percentage of O_2–Hb.

The apparatus used for making these measurements of absorption was a Hilger constant deviation wave-length spectrometer with a

Nutting polarization photometer (Pl. 1, B). The spectrometer, A, serves to disperse the light, making it possible to select the wavelength of light wherein a suitable difference of absorption occurs, and where it can best be measured. The photometer, B, measures that absorption and indicates it in the numerical values which serve as a basis for calculation. The values on the apparatus were read directly in extinction coefficients ($E = -\log T$, where E is the extinction coefficient and T the transmission). The technique in making analyses is to place a cell, C, containing the blood, which has been obtained from a puncture wound in the finger, and diluted 1:100 (0.1 c. c. to a volume of 10 c. c.) with 0.4 per cent ammonia, in front of the aperture to the right as viewed in the figure. As observed through the slit eyepiece, the field of vision is vertically tripartite, the upper and lower parts being representative of the light coming through the blood, while the central one represents that coming through a control cell of distilled water in front of the other aperture. The light coming through the distilled water can be reduced in intensity until it just equals that coming through the blood solution. When the three are of equal intensity, as judged by matching them, the extinction coefficient is read on circle D by the aid of a lens and small light E. In this manner a measure of the absorption is taken.

In making analyses, the main work is in reading the extinction coefficients due to the unknowns, then slowly bubbling a stream of O through the blood solution to displace the CO, and again reading the extinction coefficients due to the sample when determined as 100 per cent saturated with O; or by saturating CO and determining as 100 per cent saturated with CO. The former multiplied by or the latter divided by an existing constant $\left(\frac{E_{CO}}{E_{O2}} = K\right)$ between the hemoglobins will give a result representing the other hemoglobin.

The following typical set of readings will illustrate the method:

Unknown sample.	Extinction coefficient.
Oxygen bubbled for 20 minutes.....	830 (average of three).
Oxygen bubbled for 30 minutes.....	802 (average of three).
Oxygen bubbled for 40 minutes.....	791 (average of three).
	789 (100 per cent saturated with oxygen).

$$\frac{E_{CO}}{E_{O2}} = 1.42 \text{ from previous determination.}$$

Calculation:

$$\frac{(0.830-0.789)}{(0.789\times1.42-0.789)}\times100=12.4 \text{ per cent saturated with CO hemoglobin.}$$

As a daily check on the factor (1.42), two or three specimens of the oxy-hemoglobin were saturated with carbon monoxide.

PROCEDURE.

In conducting this study of the physiological effects of carbon monoxide, a procedure was followed which, in our opinion, would

afford a satisfactory accumulation of data. Before the subject entered the chamber, an examination was made as to body temperature (rectal), pulse, respiration, and general condition. During the test a similar examination was made, with the addition of the taking of blood samples at sufficient intervals to determine the rate of absorption of the carbon monoxide. At the end of a test the subject was exercised so as to bring out latent symptoms, a record of which was continued until they had abated.

As a control on conditions, the air in the gas chamber was analyzed for carbon monoxide before starting and just before completing an experiment. In some of the tests, determination of the carbon monoxide content was also made at intermediate periods. These analyses were made by the iodine pentoxide liquid air method.[4] Also, oxygen was supplied to compensate for that used by the subject (analyses of O_2 used = 98.5 per cent O_2 – 1.5 per cent N_2), and in the "long exposure," test pans of KOH, to remove the CO_2 given off, were placed on the floor before the circulating fan. An analysis of the air for these constituents was made at the end of the test.

Exposure of blood to 2 parts of CO in 10,000 of air, as calculated by Henderson,[5] may possibly produce 28.5 per cent saturation of hemoglobin when equilibrium is reached; exposure to 3 parts in 10,000 is calculated to cause 37.4 per cent saturation; and 4 parts, according to his calculations, will produce 44.4 per cent saturation. Henderson presupposes that the affinity of CO for hemoglobin is 300 times that of oxygen for hemoglobin. He further uses 15 per cent as being the concentration of oxygen in the air of the lungs. He does not claim that the figures used are more than approximately correct, but that they are sufficiently accurate for indication as to what might take place. He also calls attention to the fact that many hours of exposure are required, and that the time is really indeterminate before the circulating blood would come to complete equilibrium with the CO in air.

In our work, exposure was made to concentrations of from 2 to 4 parts of CO in 10,000 of air for several hours. The conditions and results of these tests are given in Table I. In test No. 1 the subjects were exposed to approximately 2 parts in 10,000 for 6 hours. This caused a saturation of 16 to 20 per cent of the hemoglobin with CO. This was McConnell's first test, and the percentage of hemoglobin combined with CO was somewhat greater than that in either of the other subjects. He had a slight headache, but the subjective symptoms were extremely mild, and there were no symptoms of CO poisoning in any of the subjects after the test.

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[4] Teague, M. C.: The Determination of Carbon Monoxide in Air Contaminated with Motor Exhaust Gas. Jour. Ind. & Eng. Chem., vol. 12, October, 1920, pp. 964-968.

[5] Idem.

TABLE I.—*Test for low concentrations of CO without exercise (sitting).*

Subject.	Time in minutes.	Parts CO in 10,000.	Per cent blood saturation with CO.	Respiration.	Temperature.	Pulse rate.	Symptoms. During test (time in minutes).	Symptoms. After test.	Remarks.
TEST NO. 1.									
Sayers	Start.	2.1		14	98.9	76	Before.—Feels O. K.	No symptoms.	Oxygen put in gas chamber during test. Pans containing KOH put in front of stirring fan to remove CO_2.
	60						100.—No symptoms.		
	120		8	12		72	200.—Slight tightness across forehead.		
	180						210.—Yawning.		
	240	1.8	11	15	99.4	78	250.—Slight tightness across forehead.		
	360		16	18		80	360.—All symptoms gone.		
McConnell	Start.	2.1		15	98.7	86	Before.—Feels good	No symptoms.	Analysis of air after test: O_2=20.6; CO_2=0.5.
	60						240.—No symptoms.		
	120		9	14		80	300.—Yawning.		
	180						320.—Eyes hurt, tightness across forehead.		
	240	1.8	14	15	99.2	78	360.—Drowsy, slight headache, increasing on exertion.		
	360		20	18		90			
Meriwether	Start.	2.1		14	98.3	78	Before.—Feels good	No symptoms.	
	60						240.—Yawning.		
	120		5	18		84	310.—Tightness across forehead, sleepy, yawning.		
	180						360.—Sleepy, no headache, feels lazy.		
	240	1.8	14	21	99.0	92			
	360		17	18		92			
TEST NO. 2.									
Sayers	Start.	3.1		16	99.2	74	Before.—Feels good	No ill effects on running up 40 stair steps. Slow in acting, dull nerves. Did not sleep well. Feels good next morning.	Oxygen put in gas chamber during test. Pans containing KOH put in front of stirring fans to remove CO_2. Analysis of air after test: O_2=20.8; CO_2=0.7.
	60	2.7	9				43.—Yawning.		
	120		14				65.—Yawning and sleepy.		
	180	2.8	17				165.—Yawning.		
	240	2.7	22	16	98.9	72	185.—Tightness across forehead.		
							215.—Slight headache, shortness of breath, fingers cold.		

Meriwether...	Start.	3.1	......	18	99.4	88	Before.—Slight pain in right frontal sinus.	No ill effects on running up 40 stair steps. Headache increased after walking 11 blocks; of a throbbing basal type; continued until 1 a. m. Dull and irritable following day.	
	60	2.7	12	......	......	......	155.—Yawning and slight frontal headache.		
	120	......	16	......	......	......	185.—Slight nausea on exertion.		
	180	2.8	20	......	......	......	215.—Dizzy.		
	240	2.7	24	18	99.0	82	......	......	

TEST NO. 3.

Sayers.......	Start.	2.9	......	16	99.0	74	Before.—Feels good......	Slight dizziness on running upstairs. Increasing headache during night, with chilly sensations, followed by sweating. Did not sleep well.	Oxygen put in gas chamber during test. Pans containing KOH put in front of stirring pans to remove CO_2. Analysis of air after test: O_2=21.1; CO_2=0.6.
	120	3.1	17	......	......	68	167.—Stops reading, eyes hurt, skin on forehead feels tight.		
	240	......	24	16	98.0	80	209.—Headache.		
	300	2.6	27	20	98.6	84	234.—After eating lunch slight temple headache. 250.—Headache basal in character, continuing until end of test.		
Meriwether...	Start.	2.9	......	16	98.4	88	Before.—Slight pain in right frontal sinus.	Headache exaggerated on exertion such as running upstairs. Severe headache all night. Went to hospital for sinus operation next day.	
	120	3.1	16	......	......	74	72.—Slight dizziness.		
	240	......	23	17	98.0	88	87.—Slept 15 minutes.		
	300	2.6	26	18	98.2	88	102.—Severe temple headache, slight dizziness. 234.—Ate lunch in gas chamber, headache increased. 274.—Occipital headache and very dizzy on rising.		

TEST NO. 4.

Sayers.......	Start.	4.2	......	17	99.4	84	Before.—Feels good......	Did not sleep well. Dull headache during night. O. K. next morning.	Analysis of air after test: O_2=20.6; CO=0.5.
	30	......	8	18	......	78	40.—Tightness across forehead......		
	60	......	15	19	......	78	60.—Constant desire to yawn.		
	90	......	18	18	......	80	80.—Tightness across forehead, increasing to headache on walking, feels very dull, slightly dizzy.		
	120	3.5	21	18	99.2	80	120.—Slightly dizzy, on climbing stairs palpitation and puffing. Frontal headache and dizziness.		
McConnell....	Start.	4.2	......	14	99.4	84	Before.—Feels O. K......	Throbbing headache lasting until 10.30. Irritable and dull. Didn't feel like working.	
	30	......	10	15	......	88	60.—Slight headache.		
	60	......	19	18	......	88	85.—Dull headache on walking.		
	90	......	......	19	......	88	120.—Headache, after going to bed, puffing, palpitation, and dizziness.		
	120	3.5	28	19	99.4	88			

TABLE I.—*Test on low concentrations of CO without exercise (sitting)*—Continued.

Subject.	Time in minutes.	Parts CO in 10,000.	Per cent blood saturation with CO.	Respiration.	Temperature.	Pulse rate.	Symptoms. During test (time in minutes).	Symptoms. After test.	Remarks.
TEST NO. 4—continued.									
Meriwether...	Start.	4.2	....	15	99.0	86	Before.—Feels O. K..........	After-symptoms lasting until 2 or 3 o'clock a. m. Dull and irritable next day.	
	30	....	6	17	....	84	60.—Tightness across forehead.		
	60	....	15	19	....	90	90.—Slight temple headache on walking or shaking head.		
	90	....	19	21	....	90	105.—Slight dizziness.		
	120	3.5	23	21	98.8	92	320.—All symptoms exaggerated on going upstairs. Palpitation and puffing quite noticeable.		

In test No. 2 (Table I) the subjects were exposed to approximately 3 parts of CO in 10,000 of air for four hours, remaining at rest during the entire test, at the end of which time the blood saturation was from 22 to 24 per cent. The symptoms were mild in character. The after effects were also very mild in one subject, whereas the other had symptoms, due chiefly, if not entirely, to a frontal sinus infection.

Test No. 3 (Table I) was practically a check on No. 2, with the variation of having a lunch after an exposure of 3 hours and 45 minutes, and an exposure for 5 instead of 4 hours. The lunch caused an increase in the heart rate and emphasized the symptoms of headache and slight dizziness. At the end of the test, 26 to 27 per cent of the hemoglobin of the blood was saturated with CO.

It will be noted that the blood saturation with CO at the end of four hours' exposure in test No. 3 was practically the same (22 to 24 per cent) as at the end of No. 2. It will also be noted that the rate of saturation is very much more rapid (about double) during the first hour than during any succeeding hour. After the first hour, the rate of saturation of the hemoglobin with CO was practically uniform.

The effects of exercise, after the test was completed, were noticeably more pronounced after five hours in test No. 3 than after four hours in test No. 2, due apparently to an increased hemoglobin saturation of 2 to 5 per cent and to the subject having eaten a lunch.

The subjects did not sleep well after either of the two tests, but Sayers felt practically normal the following morning. Meriwether's symptoms and after effects were probably exaggerated by or due chiefly to a frontal sinus infection for which he went to the hospital for treatment after test No. 3.

In test No. 4 (Table I) three subjects were exposed to an average of 4 parts of CO in 10,000 of air for two hours. All felt well before beginning the test, and mild symptoms, such as persistent yawning and slight headache, were noticed at the end of the first hour. After one and one-half hours' exposure, all were somewhat dizzy, and walking caused a more noticeable headache. At the end of the test (after two hours), all were somewhat dizzy, and climbing stairs caused palpitation of the heart and panting. The after symptoms were persistent headache, irritability, and inability to sleep well. On the following day the subjects were still somewhat irritable and dull. Of the hemoglobin of the blood of two subjects, 21 to 23 per cent was saturated with CO, which is no higher than in test No. 2, but the symptoms were more severe than in test No. 2. The third subject had a blood saturation of 28 per cent, which is comparable to that of subjects in test No. 3. This indicates, but of course does not definitely show, that the higher concentration of CO in air produces more severe symptoms even when the blood saturation with CO is no greater.

For any given concentration of CO in air, the rate of saturation of the hemoglobin with that gas should be much more rapid when a man is exercising than when he is at rest. This is due to the greater lung ventilation, which gives fresh and more abundant supply of CO to the blood, and to the more frequent exposure of the red blood cells to the CO, due to the more rapid circulation of the blood through the lungs.

That the above is true is borne out by the data which are given in Table II. Strenuous exercise was taken at intervals during exposure to concentrations ranging from 2½ to 4 parts of CO in 10,000 of air. The exercise, as stated earlier in this report, was taken on a bicycle ergometer, and the amount of work done was calculated in foot-pounds. While there was a great difference in the amount of work done by the subjects, the amount represents strenuous exercise for the individual working. Both men worked at the same rate—about 4,500 foot-pounds per minute—but one was able to continue the work for a full five minutes, whereas the other could work only about half as long. After each working period the subjects rested for about 15 minutes. In test No. 1 (Table II), the subjects were exposed to 2½ parts of CO in 10,000, which caused a saturation of from 14 to 16 per cent of the hemoglobin with CO at the end of one hour. The symptoms during the first half of the test were probably due chiefly to the severe exercise; during the latter half they were probably due to oxygen want in the tissues caused by both the exercise and the fact that a distinct portion of the hemoglobin combined with the CO. The subject doing the lesser amount of work in this test had more severe symptoms. This may have been caused by the fact that it was his first test of this nature, and the psychic effects emphasized the symptoms; but it was more likely due to the fact that he was in a less physically fit condition than the other subject as he was developing a frontal sinusitis.

TABLE II.—*Test on low concentrations of CO with exercise.*

Subject.	Time in minutes.	Parts CO in 10,000.	Per cent of blood saturation with CO.	Respiration.	Temperature.	Pulse rate.	Work done (in foot-pounds).	Symptoms. During test (time in minutes).	Symptoms. After test.	Remarks.
TEST NO. 1.										
Sayers	Start.	2.5		16	99.4	78	67,272	Before.—Feels good. 15.—Slight headache, little dizzy, feels effects of exercise; sweating. 30.—Headache gone, dizzy on moving. 60.—No other symptoms during test.	Pain in eyes, dull headache, head heavy.	Oxygen put in gas chamber during test. Analysis of air after test: O_2=21; CO_2=0.5
	15	2.6	3	30		130				
	30	2.6	8	26		144				
	45			28		138				
	60		14							
	After.			20	104.0	82				
Meriwether	Start.	2.5		17	99.4	96	33,826	Before.—Feels good. 15.—Yawning, dizzy, nauseated. 30.—Very dizzy, nauseated on moving; weak, air hunger, sweating profusely. 45.—Dizzy, nauseated, weak, cold hands, feels faint. 60.—No additional symptoms.	Breathed oxygen for 30 minutes; all symptoms gone except lassitude and dullness.	
	15	2.6	4	30		134				
	30	2.6	7	28		126				
	45			28		120				
	60		16							
	After.			20	99.8	90				
TEST NO. 2.										
Sayers	Start.	3.6		17	98.8	76	67,195	Before.—Feels good. 50.—Slight headache.	On running upstairs headache becomes basic. Just perceptible dizziness; did not sleep well.	Oxygen put in gas chamber during test. Analysis of air after test: O_2=20.7; CO_2=0.5.
	15			24		134				
	30	3.3	11	24		96				
	45			24		106				
	60	3.3	17			105				
	After.			18	99.4	96				
Meriwether	Start.	3.6		18	98.8	90	32,700	Before.—Frontal headache due to sinus. 35.—Slight headache, dizziness. 60.—Slightly nauseated.	Severe headache lasting until going to sleep 1.00 a.m. Feels good next morning.	
	15			34		136				
	30	3.3	13	20		90				
	45			32		144				
	60	3.3	17	26		156				
	After.			22	99.6	90				

TABLE II.—*Test on low concentrations of CO with exercise*—Continued.

Subject.	Time in minutes.	Parts CO in 10,000.	Per cent of blood saturation with CO.	Respiration.	Temperature.	Pulse rate.	Work done (in foot-pounds).	Symptoms. During test (time in minutes).	Symptoms. After test.	Remarks.
TEST NO. 3.										
Sayers	Start.	4.4	....	17	98.8	72	62,292	Before.—Feels good	Basal headache of moderate severity.	No oxygen added.
	15	....	....	24	99.2	106	....	30.—Tight feeling across forehead.		No analysis of air after test made.
	30	....	16	30	99.4	110	....	40.—Sleepy, drowsy, and yawning.		
	60	3.7	22	30	99.6	120	....	42.—Slightly dizzy on quick moving.		
								50.—Puffing, shortness of breath, palpitation of heart.		
								60.—Slight basal headache.		

In test No. 2 (Table II) the subjects were exposed to 3.3 parts of CO in 10,000 and were working at the same rate as in test No. 1. At the end of 1 hour, 17 per cent of the hemoglobin was combined with CO. The symptoms were somewhat more pronounced at the end of this test than at the end of two hours' exposure, with the subject at rest, to a slightly less concentration (test No. 3, Table I), which produced a similar saturation of the hemoglobin with CO.

Only one subject was exposed in test No. 3 (Table II) to an average of about 4 parts of CO in 10,000. The total work was slightly less than that done by this subject in either of the previous tests, but was still very strenuous. At the end of the test 23 per cent of the hemoglobin was saturated with CO. This is practically the same percentage as resulted from the exposure of the same subject at rest for two hours to a similar concentration (test No. 4, Table I), but the symptoms, as would be predicted, were somewhat more pronounced. The after effects were of moderate severity, but were more marked than they were in case of exposure to 3.3 parts of CO in test No. 2, Table II.

The effects of temperature and humidity are usually neglected when a study is being made of the physiological effects of CO, as the experiments are generally made with those factors practically normal. As it is well known that high temperature and high humidity induce greater lung ventilation and more rapid circulation of the blood, it would appear that there should be a more rapid absorption of CO by the hemoglobin when these factors are present.

Table III gives the results of the effect of very extreme conditions of temperature and humidity. A temperature of 102° to 113° F., accompanied by the high humidity used in this experiment, may produce all the symptoms recorded in this test, with the possible exception of headache, which is unusual after exposure to high temperature and humidity alone.

100373°—22——2

TABLE III.—*Test on low concentrations of CO with heat and humidity.*

Subject.	Time, in minutes.	Parts CO in 10,000.	Per cent blood saturation with CO.	Respiration.	Temperature.	Pulse rate.	Symptoms. During test (time in minutes).	Symptoms. After test.	Remarks.
Sayers	Start	3.1	......	17	98.8	72	Before.—Feels good 5.—Sweating freely. 24.—Sweating profusely. 27.—Room very uncomfortable, dizzy on rising. 38.—Room very comfortable. 40.—Sweating profusely, weak, dizzy, head feels full, slight headache. 50.—Shortness of breath, palpitation of the heart. 52.—Dull frontal headache. 60.—Slight basal headache.	Basal headache, moderate severity	No oxygen used during test. No analysis of air after test. No work done.
	10	......	......	......	......	......			
	30	......	10	30	101.4	110			
	60	3.2	16	30	102.8	120			

Temperature and humidity.

Time, in minutes.	Wet bulb.	Dry bulb.	Relative humidity.
Start	95.0	113	52
15	97.5	113	......
30	99.0	111	65
45	99.0	108	72
48	97.5	107	......
60	97.0	102	83

During the entire test the subject remained seated in a current of air moving at about 250 linear feet per minute. He wore only a suit of overalls and a pair of shoes. At the end of one hour, 16 per cent of the hemoglobin was combined with CO. This saturation is approximately equal to that found after 2 hours' exposure to a like concentration of CO (3 parts in 10,000), as that given in tests 2 and 3 (Table I), and is comparable to the effects of strenuous exercise in similar concentration as shown by Table II.

Only one test was carried out with high temperature and humidity, as the results are in concordance with those observed by the writers under similar conditions in the tests with automobile exhaust gases,[6] and the results are considered sufficiently reliable and adequate to serve as a basis for conclusions.

SUMMARY OF PHYSIOLOGICAL EFFECTS OF LOW CONCENTRATIONS OF CARBON MONOXIDE UNDER VARYING CONDITIONS.

With the subject at rest.

1. The exposure for 6 hours to 2 parts of CO in 10,000 of air caused—
   - *a.* Saturation of 16 to 20 per cent of the hemoglobin of the blood with CO.
   - *b.* Very mild subjective symptoms of CO poisoning at the end of the test.
   - *c.* No noticeable effects after the test.
2. The exposure to 3 parts of CO caused—
   - *a.* Saturation of 22 to 24 per cent of the hemoglobin with CO after 4 hours, and 26 to 27 per cent after 5 hours.
   - *b.* Symptoms at the end of 2 hours absent; after 4 hours, mild effects attributed to CO poisoning; and after 5 hours, moderate effects.
   - *c.* After effects of 4 hours' exposure mild; of 5 hours' exposure, moderate.
3. The exposure to 4 parts of CO in 10,000 caused—
   - *a.* Saturation of 15 to 19 per cent of the hemoglobin with CO at the end of 1 hour, and 21 to 28 per cent at the end of 2 hours.
   - *b.* After effects, moderate to marked.

With the subject exercising strenuously.

1. The exposure for 1 hour to 2½ parts of CO in 10,000 caused—
   - *a.* Saturation of 14 to 16 per cent of the hemoglobin with CO.
   - *b.* Moderate symptoms of CO poisoning at the end of the test.
   - *c.* After effects mild to moderate.

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[6] Teague, M. C.: The Determination of Carbon Monoxide in Air Contaminated with Motor Exhaust Gas. Jour. Ind. and Eng. Chem., vol. 12, October, 1920, pp. 964-968.

2. The exposure for 1 hour to 3.3 parts of CO in 10,000 caused—
   a. Saturation of 17 per cent of the hemoglobin with CO.
   b. Mild to moderate symptoms of CO poisoning.
   c. After effects mild to moderate.
3. The exposure for 1 hour to 4 parts of CO in 10,000 caused—
   a. Saturation of 23 per cent of the hemoglobin with CO.
   b. Moderate symptoms of CO poisoning.
   c. Moderate after effects.

With the subject at rest. Temperature and humidity high.

1. The exposure for 1 hour to 3.1 parts of CO in 10,000 caused—
   a. Saturation of 16 per cent of the hemoglobin with CO.
   b. Mild symptoms of CO poisoning.
   c. Mild to moderate after effects.

CONCLUSIONS.

1. The combination of CO with hemoglobin takes place slowly when the subject is exposed to low concentrations and remains at rest, many hours being required before equilibrium is reached.

2. The rate of combination of CO with hemoglobin takes place much more rapidly during the first hour of exposure than during any succeeding hour, with the subject remaining at rest.

3. Strenuous exercise causes much more rapid combination of CO with hemoglobin than when the subject remains at rest. The symptoms of CO poisoning are emphasized by exercise.

4. High temperature and humidity, with a given concentration of CO, cause more rapid combination of CO with hemoglobin than do normal conditions of temperature and humidity.

All symptoms and effects described in this paper are called acute in character. None of the subjects has shown any permanent deleterious effects from the exposure to CO.

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